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On-line equalization for lithium-ion battery packs based on charging cell voltages: Part 2. Fuzzy logic equalization

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HIGHLIGHTS

- We propose dissipative cell equalization (DCE) algorithm based fuzzy logic (FL).
- Cell capacities and SOCs are fuzzily identified in FL-DCE for battery pack.
- Pack capacity with FL-DCE is almost the same as DCE theoretical pack capacity.
- Adaptive FL-DCE algorithm is proposed to prevent over-equalization.
- Equalization capability of the adaptive FL-DCE algorithm is ample.

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ABSTRACT

In the first part of this work, we propose dissipative cell equalization (DCE) algorithm based on remaining charging capacity estimation (RCCE) and establish a pack model with 8 cells in series. The results show that RCCE-DCE algorithm is suitable for on-line equalization in electric vehicles (EVs) and no over-equalization happens. However, 1% pack capacity difference from the DCE theoretical pack capacity is observed with RCCE-DCE algorithm. Therefore, as the second part of the series, we propose fuzzy logic (FL) DCE algorithm based on charging cell voltage curves (CCVCs). Cell capacities and SOCs are fuzzily identified in FL-DCE algorithm by comparing cell voltages at the beginning and end of charging. Adaptive FL-DCE is further improved to prevent over-equalization and maintain the equalization capability. The simulation results show that pack capacity difference from the DCE theoretical pack capacity with the adaptive FL-DCE is smaller than that with RCCE-DCE algorithm, and the duration of the infant stage is also shorter. The proposed adaptive FL-DCE is suitable for on-line equalization in EVs and well prevents over-equalization.

1. Introduction

The inconsistency and safety issues of the battery pack system are the major problems for cells to be fully utilized. Because of the inconsistent manufacturing process, cells always have variations [1]. Cell variations enlarge due to the inhomogeneous operating environment [2]. As a consequence, power and capacity fade may occur and further result in safety issues. Cell screening process is necessary before pack construction. It diminishes cell inconsistency in the manufacturing process to some extent. Well-designed thermal management can also reduce cell inconsistency during operation. Nevertheless, on-line cell equalization is an effective means to prevent the enlargement of cell inconsistency.

In the first part of this work [3], we establish a battery pack system model to study cell variations and equalization methods. The model shows that even when the cells have good consistency, pack capacity falls significantly after several hundred cycles. And the preliminary result also shows that a capacity increase of only 2% can be achieved by non-dissipation cell equalization (NDCE) for packs with screened cell capacities. As a result, we prefer to use dissipative cell equalization (DCE) which is cheaper and easier to implement for on-line equalization. We discover and verify that remaining charging capacities (RCCs) can be on-line estimated based on the uniform charging cell voltage curve (CCVC) hypothesis [4]. As voltage- and SOC-based equalization algorithms (EAs) would suffer from over-equalization and cannot directly represent the ultimate purpose of the equalization, i.e. to maximize pack capacity, we propose DCE algorithm based on RCCE observer and prove later that RCCE-DCE algorithm is suitable for on-line equalization in electric vehicles (EVs).

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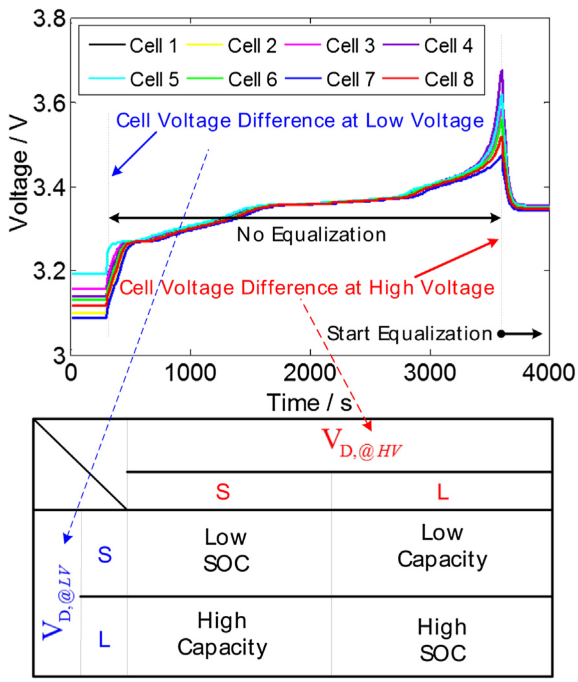


Fig. 1. Schematic diagram for the key idea of the proposed FL-EA.

However, pack capacity difference from the DCE theoretical pack capacity is observed with RCCE-DCE algorithm. Because the algorithm will force all cells to reach their charge cutoff voltage during charging, pack capacity will be constrained by all cells as a result. Regarding the ideal situation where pack capacity is constrained by the cell with the minimum capacity, the RCCE-DCE algorithm is not perfect enough. To minimize pack capacity difference from the DCE theoretical pack capacity, as the second part of the series, we propose fuzzy logic (FL) DCE algorithm based on CCVCs by comparing cell voltages at the beginning and end of charging.

EAs based on FL have been studied in literature [5–12]. D. Cadar et al. [5] proposed FL-EA based on cell voltage difference. Y. Lee et al. [6–8], R. Ugle et al. [9] and R. Ling et al. [10] further considered cell voltage difference at different cell mean voltage, and proposed FL-EAs base on cell voltage difference and cell mean voltage. Regarding cell internal resistance variation, J. Li et al. [11] proposed FL-EA base on the current and the cell voltage difference. J. Yan et al. [12] estimated cell SOCs and proposed FL-EA base on cell SOC difference and cell mean SOC.

FL-EAs in the above studies are voltage- or SOC-based EAs. As cell capacities are not considered in the algorithms, voltage- or SOC-based FL-EAs may lead to over-equalization. We suppose two cells are connected in series for example: Cell A has a capacity of 8 Ah and Cell B 12 Ah. Suppose cells are fully charged before connected in series, so the SOCs are all equal to 1 and the cell voltages are the same. After 6 Ah discharge, SOC of Cell A is 25% while SOC of Cell B is 50%. If voltage- or SOC-based FL-EAs of NDCE with ideal 100% energy transfer efficiency are implemented, Cell A need to be charged or Cell B need to be discharged gradually by the equalizer and when cells come to the “equalized state” with each 40% SOC, 1.2 Ah is transferred from Cell B to Cell A. The cells are charged in the next step, and when Cell A is fully charged, Cell B is still 80% SOC if not equalized. As a consequence, the equalizer will discharge Cell A and charge Cell B. For NDCE with ideal 100% energy transfer efficiency, no capacity losses during the equalization, but for voltage- or SOC-based FL-EAs with DCE, over-equalization lead to capacity loss and heat dissipation power increase and therefore must be prevented.

With appropriate feedback charging capacities, no over-equalization would occur using RCCE-DCE algorithm in the first part of this work. In this part, by comparing cell voltages at the beginning and end of charging, cell capacities and SOCs are fuzzily identified. The adaptive FL-DCE algorithm is subsequently proposed to prevent over-equalization and maintain the equalization capability.

2. FL-DCE based on CCVCs

The objective of pack capacity-based EAs for DCE is to make full use of the cell with the minimum capacity. Nevertheless the accurate cell SOCs and capacities are difficult to estimate on-line. As cell voltages directly reflect cell variation and CCVCs are easily to be achieved during EV charging, we use CCVCs to fuzzily identify cell SOCs and capacities. The key idea of the proposed FL-EA is demonstrated in Fig. 1. Once an EV begins the charging process, cell voltages are recorded and cell voltage difference at the beginning of charging $V_{D,@LV}$ is achieved by comparing to the minimum voltage at the beginning of charging. Cell voltage difference at the end of charging $V_{D,@HV}$ is similarly achieved by comparing to the minimum voltage at the end of charging. The equalizer is shut off during the charging process so as to accurately record the cell voltages. Equalization is started after FL-EA calculates the equalization currents for each cell using the achieved $V_{D,@LV}$ and $V_{D,@LV}$. FL-EA uses $V_{D,@LV}$ and $V_{D,@LV}$ to fuzzily identify cell capacities and SOCs. In the schematic illustration of Fig. 1, the achieved $V_{D,@LV}$ and $V_{D,@LV}$ are sorted with label “small (S)” and “large (L)”. Cells are subsequently categorized into 4 groups:

a) Low SOC: $V_{D,@LV} = S$ and $V_{D,@HV} = S$. A small voltage difference between the cell voltage and the minimum voltage at the beginning of charging indicates that the cell tends to be fully discharged at the end of discharging; A small voltage difference between the cell voltage and the minimum voltage at the end of charging indicates that the cell tends to be uncharged at the end of charging. The whole process reveals that the cell has a low SOC and a normal capacity. The equalizer should charge the cell for equalization. But for DCE, as the equalizer cannot charge cells, the cell should not be discharged by the equalizer to prevent over-equalization.
b) Low capacity: $V_{D,@LV} = S$ and $V_{D,@HV} = L$. A small voltage difference between the cell voltage and the minimum voltage at the beginning of charging indicates that the cell tends to be fully discharged at the end of discharging; A large voltage difference between the cell voltage and the minimum voltage at the end of charging indicates that the cell tends to be fully charged at the end of charging. The whole process reveals that the cell has a low capacity and pack capacity is likely to be constrained by the cell. If the cell has the minimum voltage at the beginning of charging and has the maximum voltage at the end of charging, we may infer that the cell approaches the minimum cell capacity and pack capacity also approaches the minimum cell capacity which is DCE theoretical pack capacity. Equalization can be stopped.
c) High capacity: $V_{D,@LV} = L$ and $V_{D,@HV} = S$. A large voltage difference between the cell voltage and the minimum voltage at the beginning of charging indicates that the cell tends to be undischarged at the end of discharging; A small voltage difference between the cell voltage and the minimum voltage at the end of charging indicates that the cell tends to be uncharged at the end of charging. The whole process reveals that the cell has a high capacity and no equalization is needed.

d) High SOC: $V_{D,@LV} = L$ and $V_{D,@HV} = L$. A large voltage difference between the cell voltage and the minimum voltage at the beginning of charging indicates that the cell tends to be undischarged at the end of discharging; a large voltage difference between the cell voltage and the minimum voltage at the end of charging indicates that the cell tends to be fully charged at the end of charging. The whole process reveals that the cell has a high SOC and a normal capacity. As a result, the cell should be equalized by discharging.

Based on the above analysis, we propose FL-DCE algorithm in Fig. 2. The inputs of the FL system are the voltage differences between all cell voltages and the minimum voltage at the beginning and end of the charging $V_{D,@LV}$ and $V_{D,@HV}$. The outputs are the equalization currents of all cells I_E. We use the same equalization time for all cells, so the desired equalization currents I_E accord with the equalization capacity needed. The FL system consists of 4 parts, namely fuzzification, defuzzification, rule base and inference engine. The numerical inputs of the voltage differences $V_{D,@LV}$ and $V_{D,@HV}$ are converted into fuzzy variables by the fuzzifiers. Take Fuzzifier (LV) in Fig. 2 for example, $V_{D,@LV}$ at the beginning of charging is converted to into fuzzy variables μ_{LV}, i.e. $\mu_{LV} = Fuz_{LV}(V_{D,@LV})$, where Fuz_{LV} is the fuzzy operator. The membership functions are also described in the figure, where $V_{D,@LV}$ is divided into 6 fuzzy sets. For example, $\mu_{LV} = Fuz_{LV}(V_{D,@LV}) = 2$ is the fuzzy variable results from $V_{D,@LV}$, when 10 mV $\le V_{D,@LV} <$ 15 mV. Because for $LiFePO_4$ cells, voltage difference at the end of charging is usually larger than that at the beginning of charging due to charging polarization at the end of charging, fuzzy sets for $V_{D,@HV}$ has a wider voltage difference range. For example, $\mu_{HV} = 2$ is the fuzzy variable results from $V_{D,@HV}$, when 10 mV $\le V_{D,@LV} <$ 25 mV. The normal FL typically has a pre-constructed rule base with a tabular inference engine. We adopt a simple inference engine, i.e. $\mu_i = \mu_{LV} \times \mu_{HV}$ where μ_i is the fuzzy output. With our inference engine, we will achieve the equalization result which coincides with the analysis in Fig. 1. The cells in the 4 groups (marked as a b c d) mentioned above will be $\mu_a = \mu_b = \mu_c = 0$ and $\mu_d = 25$ using the simple inference engine if "*S*" is 0 and "*L*" is 5 as defined in the fuzzifiers. And after defuzzification, Cell a b and c will have no equalization current and Cell d will be equalized at the nominal equalization current. The defuzzification process is expressed in equation (1) as follows,

$$\boldsymbol{I}_E = \begin{cases} I_0 \cdot \boldsymbol{\mu}/\max(\boldsymbol{\mu}) & \max(\boldsymbol{\mu}) \neq 0 \\ 0 & \max(\boldsymbol{\mu}) = 0 \end{cases} \quad (1)$$

where μ is the fuzzy output of equalization currents, I_E is equalization currents for all cells and I_0 is the nominal equalization current.

The control system of the proposed FL-DCE is further displayed in Fig. 3. The control cycle of the FL-DCE algorithm is a battery pack full charging cycle. The algorithm ensures no equalization during charging. The obtained cell voltage differences at the beginning and end of the charging are used in the FL block to generate equalization currents for all cells using equation (1). One single cycle equalization cannot guarantee all cells will be fully charged because the nominal equalization current is limited by circuit design. Nevertheless, with the ongoing cycles, pack capacity will ultimately approach the DCE theoretical pack capacity. Compared to the RCCE-DCE algorithm in the first part of this work, FL-DCE algorithm does not force all cells to their charge cutoff voltage. The charging and discharging process will only be constrained by the cell with minimum cell capacity if pack capacity reaches DCE theoretical pack capacity.

3. Simulation results and discussion

3.1. Preliminarily simulation results

Pack A, B, C and D in the 4 scenes with different cell variations in Part 1 are simulated (Sim11, Sim12, Sim13 and Sim14 respectively) using the proposed FL-DCE algorithm so that the simulation results can compared with those using RCCE-DCE algorithm in Part 1. The nominal equalization current I_0 in equation (1) is set to 20 mA and the equalization time is 1 h which are the same as in Part 1. The maximum equalization capacity is 20 mAh accounting for approximately 3‰ of pack capacity. Each simulation lasts 450 standard cycles.

Pack capacities using the proposed FL-DCE algorithm in the 4 packs are compared with those using RCCE-DCE algorithm in Fig. 4. The red curves stand for pack capacities with RCCE-DCE (Sim2, Sim4, Sim6 and Sim8 in Part 1), the green curves show pack capacities with FL-DCE (Sim11, Sim12, Sim13 and Sim14) and the dash-dot black curves present the DCE theoretical pack capacity. Compared to RCCE-DCE, pack capacities with FL-DCE have little difference from DCE theoretical pack capacity except for slight fluctuations.

Pack capacities of the simulations in Fig. 4 also show that the periods of the infant stages with the proposed FL-DCE algorithm are shorter than those with RCCE-DCE algorithm. Capacities of the infant pack based on RCCE-DCE algorithm stay or even fall at the beginning, because RCCE-DCE algorithm forces all cells to the fully charged state at the end of charging, while in practice some cells with higher capacities does not need to be fully charged in order to make full use of pack capacity. The proposed FL-DCE algorithm fuzzily estimate cell capacities and SOCs and the cells which constrain pack capacity will be immediately equalized, so pack capacity rises quickly in the infant stage. Fig. 4 shows that the infant stages end in less than 10 standard cycles.

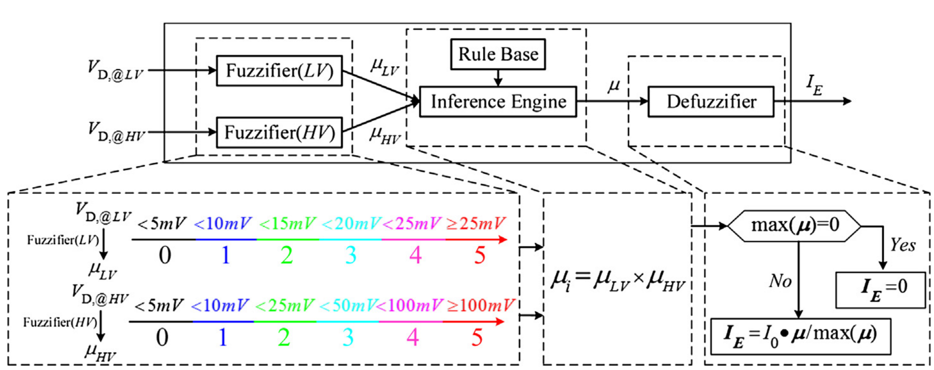


Fig. 2. Flowchart of FL-DCE algorithm.

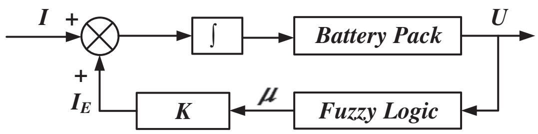


Fig. 3. Schematic diagram for the control system of FL-DCE.

CCVCs of Pack A after the infant stage using the proposed FL-DCE algorithm (Sim11) and RCCE-DCE algorithm (Sim2) respectively are further compared in Fig. 5. Fig. 5(a) plots CCVCs in one charging cycle where RCCE-DCE algorithm thinks Pack A reaches the equalized state. Cell voltages at the end of charging in the dashed green rectangle show that all cells have reached the charge cutoff voltage at the end of charging. Hence, the objective of RCCE-DCE algorithm is achieved, and no further equalization happens. Cell voltages at the beginning of charging in the dashed blue rectangle show Cell 2 has the minimum voltage and Cell 5 the maximum which are also in accordance with their capacities. Pack capacity is not ideally the same as DCE theoretical pack capacity in Sim2, because the internal resistances vary and when cells reach the charge cutoff voltage, cells with larger internal resistances are actually not fully charged. Fig. 5(b) plots CCVCs in one charging cycle where the proposed FL-DCE algorithm thinks Pack A reaches the equalized state. Cell voltages at the end of charging in the dashed green rectangle show observable voltage differences. Cell 2 reaches the charge cutoff voltage and Cell 7 has the minimum voltage. $V_{D,@HV}$ of Cell 5 is less than 5 mV, so no equalization current is need for Cell 5. $V_{D,@HV}$ of other cells are larger than 5 mV. Cell voltages at the beginning of charging in the dashed blue rectangle show that $V_{D,@LV}$ of Cell 5 is larger than 5 mV and $V_{D,@LV}$ of other cells are less than 5 mV. According to the proposed FL-DCE algorithm, none of the cells require equalization currents. We may also infer that Cell 5 has a high capacity which belongs to Group c) discussed in Chapter 2. The inference is also in accordance with capacities in the simulation setting. Compared to RCCE-DCE, it is easier for the proposed FL-DCE to reach the equalized state as the equalized state of RCCE-DCE is only a special case of the proposed FL-DCE. And this is also one of the reasons that the infant stage of RCCE-DCE is longer than the proposed FL-DCE, as the equalized state of RCCE-DCE requires more equalization capacities during the infant stage. As pack capacity is only constrained by Cell 2 in Fig. 5(b) at the end of charging, pack capacity is thus the same as the capacity of Cell 2 which is also the DCE theoretical pack capacity for Pack A.

Pack capacities using the proposed FL-DCE in Sim12, Sim13 and Sim14 have larger fluctuations than using RCCE-DCE, which are mainly caused by over-equalization. Significant fluctuations of pack capacity in Sim13 are observed. And thus, we further investigate the equalization currents and total equalized capacities in Sim13 depicted in Fig. 6. Cell equalization currents of the first 100 standard cycles are plotted in Fig. 6(a). As no equalization capacity feedback is used in FL-DCE, the maximum equalization current in each cycle is set to the nominal equalization current I_0. Because the nominal equalization current I_0 is relatively too large for Pack C, cell equalization capacities in one cycle are too large that the equalizer works intermittently. As a consequence, the heat dissipation power will be high when the equalizer works. Over-equalization happens because of the relatively large equalization current: Cell 6 should not be equalized after the infant stage as it is considered to be the worst cell after the infant stage due to its lowest coulombic efficiency, but in Fig. 6(a), Cell 6 is equalized around the 30th standard cycle. Fig. 6(b) also indicates over-equalization as the total equalized capacity of Cell 6 increases after the infant stage.

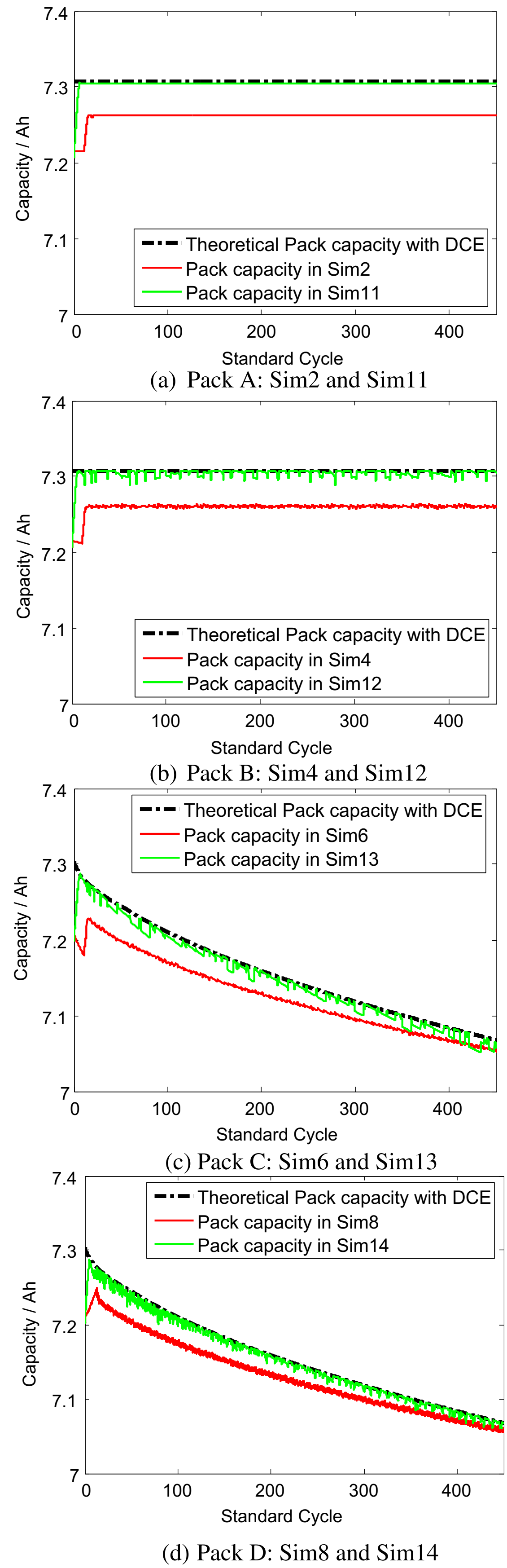
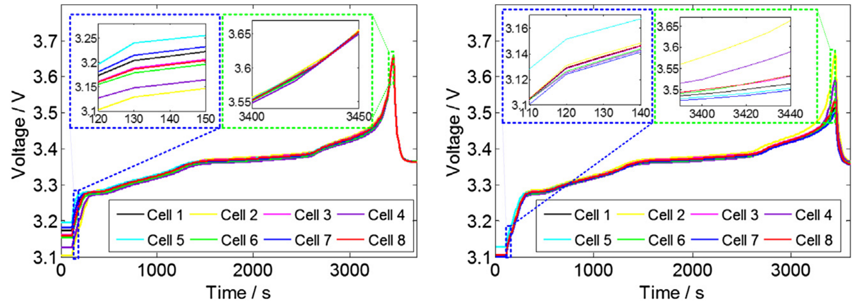
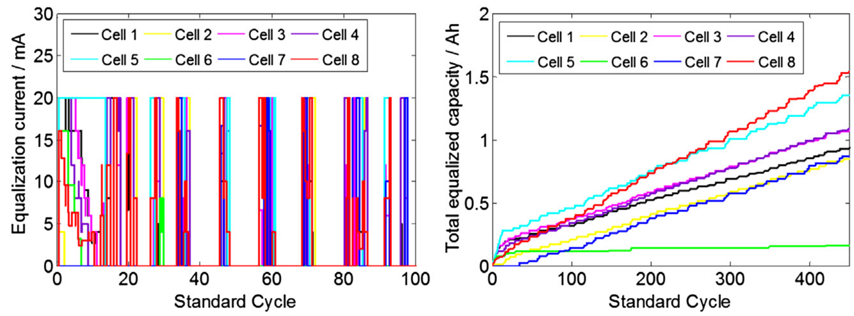


Fig. 4. Pack capacities with the proposed FL- and RCCE-DCE in different scenes (a) Pack A: Sim2 and Sim11 (b) Pack B: Sim4 and Sim12 (c) Pack C: Sim6 and Sim13 (d) Pack D: Sim8 and Sim14.



(a) Pack A: Sim2 (b) Pack A: Sim11

Fig. 5. CCVCs of Pack A after the infant stage using different equalization algorithms (a) Pack A: Sim2 (b) Pack A: Sim11.



(a) Equalization currents (b) Total equalized capacities

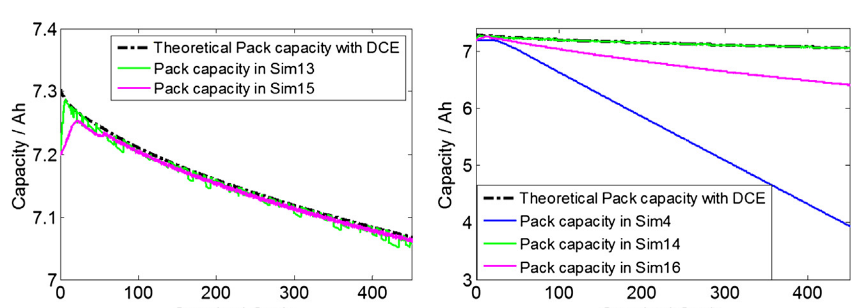
Fig. 6. Cell equalization currents and total equalized capacities in Sim13 for Pack C using FL-DCE algorithm with nominal equalization current I0 = 20 mA (a) Equalization currents (b) Total equalized capacities.

3.2. Over-equalization prevention

Over-equalization happens when no equalization capacity feedback is used in FL-DCE and the nominal equalization current I_0 is too large for its pack. To prevent over-equalization, an immediate method is to lower the nominal equalization current I_0. Thus, a nominal equalization current $I_0 = 5$ mA is subsequently used in Sim15 for Pack C and the achieved pack capacity is compared to Sim13 in Fig. 7(a)(a). Pack capacity in Sim15 is almost overlapped with DCE theoretical pack capacity and shows much smaller fluctuations compared to that in Sim13, though a smaller nominal equalization current lead to a longer infant stage of approximately 20 standard cycles.

We further investigate cell equalization currents and total equalized capacities in Sim15. Cell equalization currents of the first 100 standard cycles are plotted in Fig. 8(a). No equalization current of Cell 6 is observed after the infant stage. And Fig. 8(b) clearly shows that no equalization current generates after the infant stage as the total equalized capacity does not increase for Cell 6. This indicates that no over-equalization happens in Sim15 when the nominal equalization current I_0 is set to 5 mA. Compared to Sim13 in Fig. 6, the equalizer works continuously and the total equalized capacities are less in Sim15. As a result, the heat dissipation power is lowered.

Over-equalization is prevented by directly lowering the nominal equalization current. But this also increases the infant stage and we can also predict that an equalization capability drop happens by lowering the nominal equalization current. We exam pack capacity in Sim16 using FL-DCE with a nominal equalization current $I_0 = 5$ mA for Pack D which is extremely inconsistent with a large coulombic efficiency difference. Pack capacity in Sim16 is shown in Fig. 7(b) using the magenta curve. Though FL-DCE works and



(a) Pack C: Sim13 and Sim15 (b) Pack D: Sim4, Sim14 and Sim16

Fig. 7. Pack capacities of Pack C and D using FL-DCE with different nominal equalization currents (a) Pack C: Sim13 and Sim15 (b) Pack D: Sim4, Sim14 and Sim16.

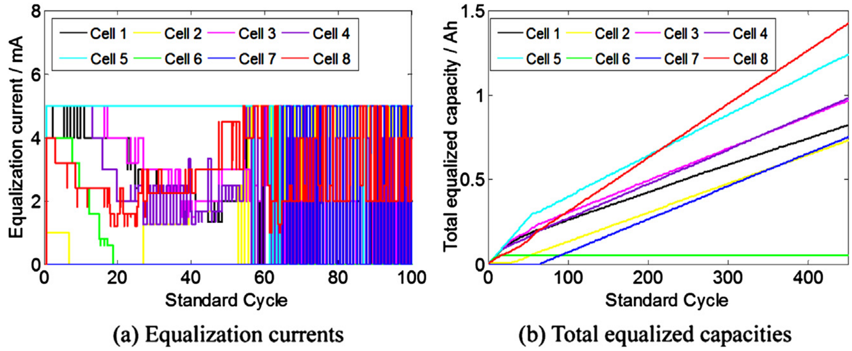


Fig. 8. Cell equalization currents and total equalized capacities in Sim15 for Pack C using FL-DCE algorithm with nominal equalization current I0 = 5 mA (a) Equalization currents (b) Total equalized capacities.

diminishes pack capacity drop compared to Sim4 which is not applied with any equalization, pack capacity cannot keep up with the DCE theoretical pack capacity as the equalization capability is insufficient.

3.3. Adaptive equalization based on fuzzy logic

From the above analysis, we discover that an appropriate nominal equalization current is important for FL-DCE algorithm. A large nominal equalization current is ample in equalization capability but might lead to over-equalization and heat dissipation problem if it is applied in packs with good cell consistency, while a small nominal equalization current can efficiently prevent over-equalization but lead to a long infant stage and its equalization capability might be insufficient for packs with unfavorable cell consistency. However, the consistency of the packs cannot be identified before the algorithm is implemented and also the consistency of the packs changes with time. Therefore, an appropriate nominal equalization current for FL-DCE cannot be preset according to the battery pack consistency. Hence, we propose an adaptive FL-DCE algorithm to overcome the above disadvantage. The adaptive FL-DCE algorithm is improved by revising the feedback factor K, which is determined by the maximum value of fuzzy output equalization currents μ. The adaptive "nominal equalization current" I_0' is subsequently determined by feedback factor K. In our simulation, the feedback factor K is calculated as

$$K = \begin{cases} I_0'/\max(\boldsymbol{\mu}) & \max(\boldsymbol{\mu}) \neq 0 \\ 0 & \max(\boldsymbol{\mu}) = 0 \end{cases} \tag{2}$$

where

$$I_0' = K_0 I_0 \tag{3}$$

$$K_0 = \begin{cases} 0.25 & \max(\boldsymbol{\mu}) \in [1,5] \\ 0.5 & \max(\boldsymbol{\mu}) \in [6,10] \\ 0.75 & \max(\boldsymbol{\mu}) \in [11,15] \\ 1 & \max(\boldsymbol{\mu}) \in [16,25] \end{cases} \tag{4}$$

I_0 in equation (3) is set to 20 mA in order to compare the adaptive FL-DCE algorithm with RCCE-DCE algorithm. The adaptive FL-DCE algorithm is implemented in Sim17 for Pack D. Pack capacities of Sim8 with RCCE-DCE algorithm and Sim17 with the adaptive FL-DCE algorithm are plotted in Fig. 9. The red curve shows pack capacity with RCCE-DCE algorithm, the magenta curve stands for pack capacity with the adaptive FL-DCE algorithm and the dash-dot black curve presents the DCE theoretical pack capacity. Fig. 9 clearly indicates that equalization capability of the adaptive FL-DCE algorithm is ample. Pack capacity difference between the adaptive FL-DCE algorithm and DCE theoretical pack capacity is smaller compared to RCCE-DCE algorithm and also the infant stage with the adaptive FL-DCE algorithm is shorter.

Fig. 10 further investigate cell equalization currents and total equalized capacities in Sim17. Cell equalization currents of the first 100 standard cycles are plotted in Fig. 10(a). During the infant stage, the algorithm thinks the pack is terribly inconsistent due to the large fuzzy output equalization currents μ. As a consequence, K_0 in equation (4) is set to 1, corresponding to the adaptive "nominal equalization current" $I_0' = 20$ mA. After the infant stage, the algorithm thinks the pack is better as μ decreases, so K_0 in equation (4) becomes 0.5 or even 0.25 corresponding to the adaptive "nominal equalization current" I_0' 10 mA or 5 mA. The large adaptive "nominal equalization current" I_0' reduces the infant stage and equalization capability is guaranteed as I_0' reaches 10 mA after the infant stage. Fig. 10(b) clearly shows that no equalization current generates after the infant stage as the total equalized capacity does not increase for Cell 1 which has the minimum coulombic efficiency in Pack D. This indicates that no over-equalization happens in Sim17 with the adaptive FL-DCE algorithm.

4. Conclusion

This paper is the second part of the series proposes on-line equalization algorithms for lithium-ion battery packs in EVs based on CCVCs. In the first part, we propose a suitable RCCE algorithm for on-line equalization in EVs which guarantees no over-equalization. However, pack capacity difference from the DCE

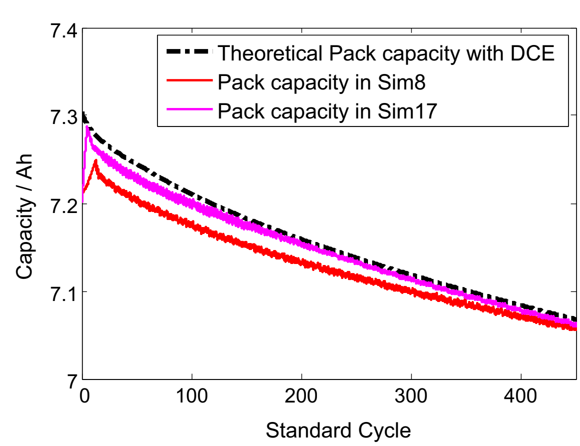
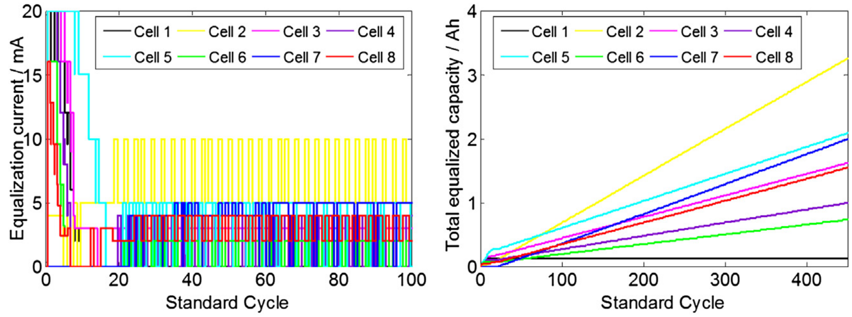


Fig. 9. Pack capacities of Pack D with RCCE-DCE algorithm in Sim8 and with the adaptive FL-DCE algorithm in Sim17.



(a) Equalization currents (b) Total equalized capacities

Fig. 10. Cell equalization currents and total equalized capacities in Sim17 for Pack D using the adaptive FL-DCE algorithm (a) Equalization currents (b) Total equalized capacities.

theoretical pack capacity is observed with RCCE-DCE algorithm. In this part, we propose FL-DCE algorithm based on CCVCs. Cell capacities and SOCs are fuzzily identified in FL-DCE algorithm by comparing cell voltages at the beginning and end of charging. With a simple inference engine, FL-DCE algorithm is deduced and implemented in the control system.

We first compare pack capacities using the proposed FL-DCE algorithm and RCCE-DCE algorithm in 4 packs at the same conditions. Because the proposed FL-DCE is intelligent in identifying cell capacities and SOCs, pack capacities with FL-DCE have little difference from DCE theoretical pack capacity except for slight fluctuations, and the periods of the infant stage with the proposed FL-DCE are also shorter than those with RCCE-DCE algorithm. However, because no equalization capacity feedback is used in FL-DCE and the nominal equalization current is too large for the packs, equalization capacities in one cycle are too large that the equalizer works intermittently and over-equalization happens. Subsequently, a smaller nominal equalization current is used in the proposed FL-DCE algorithm to prevent over-equalization. The result shows that over-equalization is effectively prevented by directly lowering the nominal equalization current. But this also increases the period of the infant stage and decreases the equalization capability. Hence, we further propose an adaptive FL-DCE algorithm improved by using an adaptive "nominal equalization current" which changes with the degree of the pack consistency. Equalization capability is proved to be ample and no over-equalization happens with the adaptive FL-DCE algorithm.

In conclusion, pack capacity with the adaptive FL-DCE algorithm is almost the same as DCE theoretical pack capacity and the infant stage ends faster than that with RCCE-DCE algorithm. Equalization capability is ample and no over-equalization happens with the adaptive FL-DCE. It fits packs with different pack consistency and therefore is applicable for on-line equalization in battery packs of EVs.

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